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**Theoretical Interpretations of Neutrino Experiments**

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## ABSTRACT

The main objective is to summarize neutrino and antineutrino induced reactions with special emphasis on recent theoretical and experimental developments. The first part deals primarily with total cross sections. It is shown that Bjorken's scaling hypothesis for the weak structure functions provides a powerful means for analyzing high energy lepton-hadron scattering. It predicts the linear rise of the total cross sections and provides bounds for the ratio  $\frac{\sigma(\bar{\nu} + N \rightarrow \mu^+ + x)}{\sigma(\nu + N \rightarrow \mu^- + x')}$ . A recent determination of this ratio at CERN indicates that it is near the physical boundary, which in turn has several consequences. A comparison of such detailed information with the quark-parton and light-cone models reveals a remarkable consistency between theory and experiment.

The second topic deals with the revived interest in neutral currents. Within the last year new experimental bounds have been established for several processes. Their interpretation in the V-A and the Weinberg theories are discussed. In theories of the Weinberg-type limits on neutral currents are obtained free of any dynamical assumption. A survey of existing results and prospects for future experiments are presented.

## INTRODUCTION

A unique role among the elementary particles is played by neutrinos (and antineutrinos), because they are the only particles which have only weak interactions. For this reason neutrinos provide ideal beams for investigating the properties of weak interactions and for probing the structure of hadrons. Recent experiments at CERN<sup>1</sup> and Argonne<sup>2</sup> provide new and significant experimental information and their theoretical interpretation is the subject of this article.

Since there are already several excellent reviews of this field<sup>3-5</sup>, the emphasis of the present work is on recent developments. The outline is as follows. First we appeal to the scaling phenomenon and extract from the data several quantities relevant to theory. Then we describe briefly some of the theoretical ideas relevant to the experiments and lead up to a comparison between theory and experiment. Finally we discuss some of the numerous implications that these data and theoretical ideas have for other branches of high energy physics. In particular, we will concentrate on the question of the existence of neutral currents and attempt to make a comprehensive comparison between the experimental bounds and the theoretical predictions.

## TOTAL CROSS SECTIONS

The processes that we are dealing with are shown schematically in Fig. 1. The process is described in the laboratory frame. An incident neutrino with energy  $E$  hits a nucleon at rest, leading to a final muon with energy  $E'$  and a final hadronic state

with momentum  $P_n$ . When we sum over all final hadronic states, the process depends on three kinematic variables:

$E$  : incident energy

$\nu = E - E'$  : energy transfer

$q^2 = -Q^2 = 4EE'\sin^2\theta/2$  : square of the momentum transfer.

The explicit functional form of the leptonic vertex is known from the effective current-current interaction Lagrangian.

The wavy line indicates an exchange force, and may or may not correspond to a W-boson. For the remaining of this article we do not assume the exchange of an intermediate vector boson, unless otherwise stated. All the interesting structure is hidden in the hadronic vertex.

The hadronic vertex describes the absorption of a current by a hadron. Since in the experiments the targets are unpolarized, there is no dependence on the spin of the target. The current, however, is a superposition of helicity states. For a space-like current there are three polarization states. The unknown structure functions for the hadronic vertex can be chosen as three total cross sections, corresponding to the absorption of a right-handed, left-handed and scalar current, denoted respectively by

$$\sigma_R(Q^2, \nu), \sigma_L(Q^2, \nu) \text{ and } \sigma_S(Q^2, \nu) \quad (2-1)$$

The double differential cross section<sup>6,7,8</sup> for incident neutrinos is

$$\frac{d\sigma^\nu}{dQ^2 dE'} = \frac{G^2}{2\pi} \frac{E'}{E} W_2(Q^2, \nu) \left\{ 1 + \frac{\nu}{E'} (L) - \frac{\nu}{E} (R) \right\} \quad (2-2)$$

where

$$\begin{pmatrix} L \\ R \end{pmatrix} = \frac{\begin{pmatrix} \sigma_L \\ \sigma_R \end{pmatrix}}{2\sigma_S + \sigma_L + \sigma_R} \quad \text{and} \quad F_2(x) = \frac{1}{2\pi} Q^2 \frac{(1 - Q^2/2M\nu)}{(1 + Q^2/\nu^2)} (2\sigma_S + \sigma_L + \sigma_R) \quad (2-3)$$

The corresponding formula for antineutrinos is

$$\frac{d\sigma^{\bar{\nu}}}{dQ^2 dE} = \frac{G^2}{2\pi} \frac{E'}{E} \overline{W_2(Q^2, \nu)} \left\{ 1 + \frac{\nu}{E'} (\bar{R}) - \frac{\nu}{E} (\bar{L}) \right\} \quad (2-4)$$

The bar over the structure functions indicates that in general they are different from those in Eq. (2-2).

A crucial assumption for the remaining of this discussion is Bjorken's scaling phenomenon<sup>9</sup>. From Eqs. (2-2) and (2-3) we observe that  $\nu W_2(Q^2, \nu)$ ,  $(R)$  and  $(L)$  are dimensionless quantities. Consequently in the limit

$$Q^2 \rightarrow \infty \quad \text{with} \quad Q^2/2M\nu = \text{finite} \quad (2-5)$$

these functions can oscillate or approach zero, infinity, or a non-trivial function of the dimensionless ratio  $x = Q^2/2M\nu$ . A few years ago Bjorken remarkably predicted<sup>9</sup> that in the above limit the structure functions approach non-trivial functions of a single dimensionless variable

$$\begin{aligned} \nu W_2(Q^2, \nu) &\rightarrow F_2(x) \\ \begin{pmatrix} R \\ L \end{pmatrix} &\rightarrow f_{R,L}(x) \end{aligned} \quad (2-6)$$

The scaling phenomenon has been observed for limited ranges of  $Q^2$  and  $\nu$  in the electroproduction experiments of the SLAC-MIT group<sup>10</sup>. The pleasant surprise is that the structure functions approach this limit rather fast. It settles in for values of

$Q^2 \geq 2(\frac{\text{GeV}}{c})^2$ . Such tests will be extended to larger ranges of  $Q^2$  and  $\nu$  in the NAL experiments<sup>11</sup>. At this time, however, there is no direct test of scaling in neutrino induced reactions, but we do have some indirect tests which we discuss.

Theorem: 1) If all three structure functions scale<sup>9</sup>

then

$$\sigma^\nu \xrightarrow{E \rightarrow \infty} C E_\nu$$

(2-7)

$$\sigma^{\bar{\nu}} \xrightarrow{E \rightarrow \infty} C' E_{\bar{\nu}}$$

2) For targets<sup>8</sup> with equal numbers of protons and neutrons (isoscalar) the scaling of all three structure functions implies  $1/3 \leq \sigma^{\bar{\nu}}/\sigma^\nu \leq 3$  (2-8)

Proof: (i) Integrating over  $Q^2$  and appealing to scaling

$$\frac{d\sigma}{dE'} = \frac{G^2}{2\pi} 2M \left\{ \int F_2(x) \frac{dQ^2}{2M\nu} \right\} \left\{ 1 + \frac{\nu}{E'} \langle L \rangle - \frac{\nu}{E} \langle R \rangle \right\} \quad (2-9)$$

where

$$\langle L, R \rangle \equiv \frac{\int F_2(x) \langle L, R \rangle dx}{\int F_2(x) dx} \quad (2-10)$$

Thus scaling decouples the integrations of  $x$  and  $E'$ , so that the dependence in  $E'$  is explicitly exhibited. Integrating over  $E'$

$$\sigma^\nu = \frac{G^2}{2\pi} 2ME \left\{ \int F_2(x) dx \right\} \left\{ \frac{1}{2} + \frac{1}{2} \langle L \rangle - 1/6 \langle R \rangle \right\} \quad (2-11)$$

Similarly for antineutrinos.

(ii) For isoscalar targets

$$F_2(x) = \bar{F}_2(x), \quad \langle \bar{L}, \bar{R} \rangle = \langle L, R \rangle \quad (2-12)$$

by charge symmetry. Therefore

$$\frac{\sigma^{\bar{\nu}}}{\sigma^\nu} = \frac{\frac{1}{2} + \frac{1}{2} \langle R \rangle - 1/6 \langle L \rangle}{\frac{1}{2} + \frac{1}{2} \langle L \rangle - 1/6 \langle R \rangle} \quad (2-13)$$

where  $0 \leq \langle L \rangle \leq 1$ ,  $0 \leq \langle R \rangle \leq 1$  and  $\langle 2S \rangle + \langle L \rangle + \langle R \rangle = 1$ .

Eq. (2-8) now follows with the upper limit corresponding to  $\langle L \rangle = 1$  and  $\langle R \rangle = 0$ .

Fig. (2) shows the measurements from the Gargamelle collaboration<sup>1</sup>. The cross sections are consistent with a linear rise. The statistics are too limited to provide undisputed evidence in favor of the linear rise. Consequently tests of other consequences of scaling are desirable. Fig. (3) shows the ratio of the cross sections. If we assume that the total cross sections rise linearly with energy starting at 2 GeV, then their ratio is determined with good accuracy:

$$\frac{\sigma^{\bar{\nu}}}{\sigma^{\nu}} / \text{exp} = .377 \pm 0.023 \quad (2-14)$$

It is close to the lowest bound allowed by scaling.

The simplicity of the theorem is not indicative of the stringent constraints that it implies, because semileptonic interactions are not restricted by the bounds which are valid in hadronic interactions. For instance, Froissart's theorem<sup>12</sup> requires that hadronic total cross sections can grow at most like  $(\ln E)^2$ . This theorem, however, has no implications for semileptonic reactions because two of the basic assumptions required in the proof the theorem do not hold for semileptonic reactions. Namely, Froissart's theorem is based on

- (i) absence of zero mass particles
- (ii) quadratic unitarity

both of which are absent in semileptonic reactions, because we do have zero mass particles and unitarity is linear.

In addition, the Pomeranchuk theorem<sup>13</sup> refers to the hadronic part of the diagram and the ratio  $\sigma^{\bar{\nu}N}/\sigma^{\nu N}$  can be different from unity at very high energies.

### ANALYSIS OF THE CERN DATA

In view of the CERN results it seems reasonable to analyze existing data in terms of two hypotheses:

- (i) Scaling of all three structure functions
- (ii) The ratio of the cross sections is close to 1/3;

i.e.

$$\frac{\sigma^{\bar{\nu}N}}{\sigma^{\nu N}} = \frac{1}{3} (1 + \epsilon) \quad \text{with } \epsilon \ll 1. \quad (3-1)$$

Eqs. (2-13), (3-1) and the trivial identity

$$\langle R \rangle + \langle L \rangle + 2 \langle S \rangle \equiv 1 \quad (3-2)$$

imply the constraint equation<sup>14</sup>

$$\frac{\langle R \rangle}{\langle L \rangle} + \frac{3}{4} \frac{\langle S \rangle}{\langle L \rangle} = \frac{3}{8} \epsilon + O(\epsilon^2) \quad (3-3)$$

The constraint equation leads to several important consequences

$$1) \quad \langle S \rangle / \langle L \rangle \leq \frac{1}{2} \epsilon \quad (\approx 0.06) \quad (3-4)$$

in agreement with the corresponding ratio in electroproduction<sup>10</sup> and the Callan-Gross relation<sup>15</sup>.

$$2) \quad \langle R \rangle / \langle L \rangle \leq \delta = (3/8) \epsilon \quad (3-5)$$

This relation may be useful in testing the parton (light cone) relation

$$W_2(V) = W_2(A) \quad (3-6)$$

where V and A indicate the contributions arising from the vector and axial currents respectively. It has been shown<sup>14</sup> from kinematic arguments that

$$1 - 4\delta^{1/2} + 0(\delta) \leq \frac{\int F_2(V) dx}{\int F_2(A) dx} \leq 1 + 4\delta^{1/2} + 0(\delta) . \quad (3-7)$$

Present data suggest the  $\delta \approx 0.05$ , so that the above ratio is consistent with the value of one, but Eq. (3-7) is not very restrictive. An accurate determination of such a ratio is rather difficult. This ratio is important, however, because together with the Conserved Vector Current hypothesis determines the isovector contribution to electroproduction and consequently the isoscalar part.

(3) The slope of the cross section provides<sup>5</sup> the integral

$$\int F_2^{\nu N}(x) dx \approx 0.47 \pm .07 \quad (3-8)$$

where N denotes the average value per nucleon. The value in (3-8) depends on scaling of  $F_2(x)$  and  $\sigma_S/\sigma_T = 0$ .

(4) Using the method discussed in the theorem we can evaluate the mean energy carried by the muon:

$$\langle E'/E \rangle_\nu = \frac{\int \frac{E'}{E} \frac{d\sigma}{dQ^2 d\nu} dQ^2 d\nu}{\sigma_{\text{tot}}} = \frac{\frac{1}{3} + \frac{1}{6} \langle L \rangle - \frac{1}{12} \langle R \rangle}{\frac{1}{2} + \frac{1}{2} \langle L \rangle - \frac{1}{6} \langle R \rangle} \quad (3-9)$$

We can maximize and minimize this expression<sup>14</sup> subject to the constraint equation and obtain

$$\frac{1}{2} \leq \langle E'/E \rangle_\nu \leq \frac{1}{2} + \frac{1}{12} \epsilon \quad (3-10)$$

Thus the negative muon ( $\mu^-$ ) carries on the average half of the neutrino energy. Similarly we can estimate the mean energy of  $\mu^+$  in antineutrino experiments

$$\frac{3}{4} - \frac{9}{32} \epsilon \leq \langle E'/E \rangle_{\bar{\nu}} \leq \frac{3}{4} \quad (3-11)$$

The positive muon carries on the average  $\frac{3}{4}$  of the antineutrino's energy. The corresponding experimental values<sup>16</sup> are

$$\langle \frac{E'}{E} \rangle_{\nu} = .55 \pm .10$$

and

$$\langle \frac{E'}{E} \rangle_{\bar{\nu}} = .69 \pm .09$$

The results are consistent.

- (5) Using similar techniques we can estimate the integral<sup>14</sup>

$$\int x F_2(x) dx \approx \langle \frac{Q^2}{2ME} \rangle_{\nu} 2 \int F_2(x) dx \quad (3-12)$$

There is already an experimental determination<sup>17</sup> of

$$\langle \frac{Q^2}{2ME} \rangle_{\nu} \approx \frac{1}{9} \quad (3-13)$$

thus

$$\int x F_2(x) dx \approx .12 \quad (3-14)$$

- (6) From the electroproduction data we have a good estimate of the integral

$$\frac{1}{2} \int [F_2(x)^{\gamma p} + F_2(x)^{\gamma n}] dx = 0.14 \pm 0.02 \quad (3-15)$$

Consequently this together with the slopes of the neutrino cross sections lead to the ratio

$$R_1 = \frac{\int [F_2(x)^{\gamma p} + F_2(x)^{\gamma n}] dx}{\int [F_2(x)^{\nu p} + F_2(x)^{\nu n}] dx} = .30 \pm .06 \quad (3-16)$$

which is relevant to the symmetry predictions of the models.

Table 1 summarizes several of the quantities and compares them with corresponding quantities in electroproduction. In the next section we shall return to the table and interpret the comparisons in terms of some models.

### PARTON MODEL PREDICTIONS

A transparent way of presenting the theoretical ideas is in terms of the quark-parton model<sup>18-23</sup>. An equivalent presentation would be in terms of light cone singularities of current commutators<sup>24,25</sup>. To be specific we remark that all the predictions of the present section are identical in both models.

In the parton model the process is described in an infinite momentum frame. The neutrino-proton center-of-mass system is, at high energies, a good approximation of such a frame (Fig. 4). In this frame we visualize the proton being made up of a set of elementary quanta, called partons. We identify them in this section with quarks. The life time of the constituents in the center of mass frame is

$$T = \frac{2P}{\text{Constant}} \quad (4-1)$$

The time of interaction on the other hand is

$$\tau \approx \frac{1}{q_0} = \frac{4P}{2Mv(1-x)} \quad (4-2)$$

so that in the Bjorken limit

$$\tau \ll T \quad . \quad (4-3)$$

Consequently, the time of interaction becomes so short in comparison to the life of the partons, that the current

interacts with a single parton leaving the rest of them undisturbed. Partons are considered to be fundamental so that the currents measure the quantum numbers of the quarks.

In the model we can understand the experimental quantities, which have been isolated.

- 1) Scaling is a consequence of the supposition that the scattering between the neutrino and a parton carrying momentum  $xP$  is "elastic", so that  $Q^2$  and  $xP \cdot q$  are not independent variables, but satisfy

$$Q^2 = 2M\nu x \quad (4-4)$$

- 2) The small value of  $\langle S \rangle / \langle L \rangle$  given in (3-4) follows if we assign spin  $1/2$  to the partons<sup>15,8,21</sup>. For comparison we mention that in electroproduction<sup>10</sup>

$$\frac{\sigma_S}{\sigma_T} = 0.14 \pm .10 \quad \text{proton} \quad (4-5)$$

$$\frac{\sigma_S}{\sigma_T} = 0.15 \pm 0.08 \quad \text{deuteron} \quad (4-6)$$

- 3) Now that we associate partons with spin  $\frac{1}{2}$  particles we can account for the ratio of the total cross-sections

$$\frac{\sigma_{\bar{\nu}}}{\sigma_{\nu}} \approx \frac{1}{3}$$

by requiring that the momentum carried by the antipartons is small. This follows from a helicity argument. We observe that the parton or antiparton struck but the current is relativistic after the collision. The (V-A) form of the weak current guarantees that partons are "left-handed" and anti-partons "right-handed". Therefore

a right-handed current cannot interact with a parton as it is illustrated in Fig. 5. Conversely, antipartons interact only with "right-handed" currents. Thus the ratio of 1/3 follows by suppressing the contribution of the antipartons.

In the Drell-Yan model<sup>20</sup> for  $x \ll 1$  the current interacts with a bare proton and the corresponding differential cross sections are again in the ratio 1:3. This relation however holds in a limited region of  $x$ . The contribution to the cross section from this limited region of phase space is very very small so that the coincidence of the ratios is accidental.

- 4) The models expect the equality of contributions of the axial and vector currents to  $W_2(Q^2, \nu)$ . Within the model the V and A contributions to  $W_2$  arise from the Born diagrams shown in Fig. 6. Neglecting masses the equality

$$W_2(V) = W_2(A)$$

follows from the trivial identity

$$\bar{U}(P)\gamma_\nu\gamma_5(\not{P}+\not{q})\gamma_\mu\gamma_5U(P) = \bar{U}(P)\gamma_\nu(\not{P}+\not{q})\gamma_\mu U(P) \quad (4-7)$$

- 5) Different moments  $\int x^n F_2^{\nu N}(x) dx$  can be compared with corresponding moments in electroproduction. Such comparisons are made by virtue of the following two properties:
- (i) The parton (light-cone) relation  $W_2(V) = W_2(A)$ .
  - (ii) The parton (light-cone) suggestion that the isoscalar contribution  $F_2^{\gamma p} + F_2^{\gamma n}$  is less than 10%. The small isoscalar contribution is not inherent in the model, but it follows from an additional and reasonable

assumption<sup>26,27</sup>, to be described later when we describe the symmetry relations.

It follows from (i) and (ii) that

$$4[F_2^{\gamma p}(x) + F_2^{\gamma n}(x)] \approx F_2^{\nu p}(x) + F_2^{\nu n}(x) \quad (4-8)$$

where the approximate sign indicates the ambiguity associated with the isoscalar contribution. This relation is expected to hold to within 10-20%. Table (1) summarizes the comparisons between electron and neutrino induced reactions. The last two rows compare the zeroth and first moment of  $F_2(x)$ . The agreement is good.

#### 6) Symmetry Relations

By assigning to the partons the quantum numbers of the quarks we introduce six independent distribution functions. They correspond to the probabilities  $f_p(x)$ ,  $f_n(x)$  ... of finding in the proton a p, n...,  $\bar{\lambda}$ -type quark carrying a fraction x of its momentum. In principle, however, we have many more measurable quantities so that several relations between the structure functions follow. In addition since cross sections are positive quantities we expect several positivity relations. We discuss some of these well known relations.

##### (i) The Llewellyn-Smith relation<sup>28</sup>

$$12[F_1^{\gamma p}(x) - F_1^{\gamma n}(x)] = F_3^{\nu p}(x) - F_3^{\nu n}(x) \quad (4-9)$$

cannot be tested with available data because there are no experiments on individual proton targets.

Since it is a point by point relation it also holds

when we multiply by  $x^n$  ( $n \geq 0$ ) and integrate. For  $n = 0$  it gives the interesting result<sup>29</sup>

$$\frac{\sigma_{\bar{\nu}p}}{\sigma_{\nu d}} + \frac{\sigma_{\nu p}}{\sigma_{\nu d}} \approx .55 \pm .09 \quad (4-10)$$

This relation depends on relative  $\nu$  and  $\bar{\nu}$  fluxes and can be measured in the early NAL experiments.

(ii) An integral form of the Llewellyn-Smith inequality<sup>28</sup>

$$\frac{F_2^{\gamma p} + F_2^{\gamma n}}{F_2^{\nu p} + F_2^{\nu n}} \geq \frac{5}{18} \quad (4-11)$$

was estimated in Eq. (3-16). The experimental value is slightly larger than the theoretical lower bound. The proximity to the lower bound is understood in terms of an argument presented by Feynman<sup>26</sup> at the Balaton Conference. It is conjectured that

$$\int x(f_{\lambda} + f_{\bar{\lambda}}) dx \leq \min. \left\{ \int x(f_p + f_{\bar{p}}) dx, \int x(f_n + f_{\bar{n}}) dx \right\} \quad (4-12)$$

which in turn implies that  $R_1$  in (3-16) cannot exceed 5/18 by more than 10%. Lipkin also arrives<sup>27</sup> at the same conclusion by arguing that the scattering on a nucleon of the " $\phi$ " component of the photon is not stronger than that of the " $\rho$ " or " $\omega$ " components. He obtains

$$R_1 = \frac{11}{36} (1 + \xi) \quad \text{with} \quad |\xi| \leq \frac{1}{11} \quad (4-13)$$

(iii) Specializing to proton and neutron targets Nachtmann<sup>30</sup> observed that the electroproduction structure functions must satisfy

$$4 \geq y = \frac{F_2^{\gamma n}(x)}{F_2^{\gamma p}(x)} \geq 1/4 \quad (4-14)$$

Recent data<sup>31</sup> by the MIT group is consistent with this relation. Fig. 7 shows the experimental results. Whenever the ratio  $y(x)$  is known<sup>32</sup>, we can improve the bound on the neutrino structure functions.

$$Z \equiv \frac{F_2^{\nu n}}{F_2^{\nu p}} \geq \frac{1}{2} + \frac{1}{2} \frac{6 - 9y}{4y - 1} \quad (4-15)$$

The solid curve in Fig. 7 indicates a lower bound for this ratio. The qualitative features are easily understood as it is shown in Fig. 8. As  $x \rightarrow 1$  the current sees one quark, which carries all the momentum. For the ratio to be  $1/4$  this must be a p-type quark within the proton. In the neutrino case  $F_2^{\nu p}$  vanishes, because a p-type quark cannot absorb a positive unit of charge. On the other hand  $F_2^{\nu n}$  is finite and the ratio is very large.<sup>33</sup>

- 7) We now summarize the implications of the data for the parton model (i) The Gargamelle Collaboration indicates<sup>5</sup> that

$$\frac{\sigma^{\nu}(\Delta s=1)}{\sigma^{\nu}(\Delta s=0)} \approx 0.01 \quad \text{and} \quad \frac{\sigma^{\bar{\nu}}(\Delta s=1)}{\sigma^{\bar{\nu}}(\Delta s=0)} \approx 0.04 \quad (4-16)$$

Small corrections are made to the data and the quoted values will from now on refer to  $\Delta s=0$  transitions.

(ii) The ratio

$$\frac{\sigma^{\bar{\nu}}}{\sigma^{\nu}} = \frac{1}{3} (1+\epsilon) \quad \text{with} \quad \epsilon \ll 1 \quad (\epsilon \approx 0.15) \quad (4-17)$$

implies

$$\int x [f_{\bar{p}}(x) + f_{\bar{n}}(x)] dx \leq \frac{3}{8} \epsilon \int x [f_p(x) + f_n(x)] dx \quad (4-18)$$

The Momentum carried by  $\bar{p}$  and  $\bar{n}$  quark is small.

(iii) Experimental estimates indicate

$$\frac{\int [F_2^{\gamma p} + F_2^{\gamma n}] dx}{\int [F_2^{\nu p} + F_2^{\nu n}] dx} = 0.30 \pm 0.06 \leq 5/18 + \delta \quad (4-19)$$

This in turn restricts the contribution of the strange quarks

$$\frac{\int x [f_\lambda(x) + f_{\bar{\lambda}}(x)] dx}{\int x [f_p(x) + f_n(x)] dx} \leq 9\delta \approx 0.72 \quad (4-20)$$

The constraint on the strange quarks is not very restrictive, but it is consistent with the conjecture discussed in (6,ii).

(iv) It was reported at the Cornell Conference<sup>34</sup> that

$$\frac{\int F_2^{\gamma n}(x) dx}{\int F_2^{\gamma p}(x) dx} \approx \frac{2}{3} \quad (4-21)$$

This numerical value is approximately equal in magnitude to the ratio of the magnetic moments of the proton and neutron, but it has the opposite sign. It implies

$$\frac{1}{2} - \xi \lesssim \frac{\int x f_n(x) dx}{\int x f_p(x) dx} \lesssim \frac{1}{2} \quad \text{where } \xi \approx 0.11 \quad (4-22)$$

We have determined the contribution of the anti-quarks to be small (Eq. 4-18) and the ratio arising from the contributions of n- and p-type quarks is determined (Eq. 4-22). Thus we can predict the individual cross sections on proton and neutron targets.

(v) The cross sections for  $\nu$ -parton and  $\bar{\nu}$ -parton are

$$\frac{d\sigma}{dQ^2 dv}(\nu-p) = \frac{G^2}{\pi} \delta\left(\nu - \frac{Q^2}{2M}\right) \quad \text{and} \quad (4-23a)$$

$$\frac{d\sigma}{dQ^2 dv}(\bar{\nu}-p) = \frac{Q^2}{\bar{\nu}} \delta\left(\nu - \frac{Q^2}{2M}\right) \left(1 - \frac{\nu}{E}\right)^2 \quad (4-23b)$$

Multiplying by the appropriate distribution functions we obtain

$$\sigma^{\nu p} = \frac{G^2}{\pi} s \int x f_n(x) dx; \quad \sigma^{\nu n} = \frac{G^2}{\pi} s \int x f_p(x) dx \quad (4-24)$$

$$\sigma^{\bar{\nu} p} = \frac{G^2}{\pi} s \frac{1}{3} \int x f_p(x) dx \quad \text{and} \quad \sigma^{\bar{\nu} n} = \frac{G^2}{\pi} s \frac{1}{3} \int x f_n(x) dx$$

The antiparton contributions have been neglected by virtue of Eq. (4-18).

Combining the results of this subsection we arrive at the main conclusions

$$\frac{\sigma^{\nu n}}{\sigma^{\nu p}} \approx \frac{\sigma^{\bar{\nu} p}}{\sigma^{\bar{\nu} n}} \approx 3 \frac{\sigma^{\bar{\nu} p}}{\sigma^{\nu p}} \approx 2 \left(1 \pm \frac{0.11}{0.00}\right) \quad (4-25)$$

The above estimates suggest

$$\sigma^{\nu n} : \sigma^{\nu \bar{p}} : \sigma^{\bar{\nu} p} : \sigma^{\bar{\nu} n} \approx 6 : 3 : 2 : 1 \quad (4-26)$$

In view of this result, we identify the ratio in Eq. (4-10) as 5/9.

Numerical estimates for the cross sections have also been discussed recently by Gourdin<sup>36</sup> in the equipartition version of the parton model. He also obtained ratios consistent with those in Eq. (4-25) and (4-26). The present analysis indicates

that accurate determination of the ratio in Eq. (4-21) can determine the ratios in (4-25). One of the objectives of the model has been the determination of several processes in terms of six distribution functions. A measurement<sup>34</sup> of (4-21) to 5-10% will determine all the integrals of the form  $\int x f_i(x) dx$ , which are relevant to the neutrino total cross sections. Such a determination will predict the ratio of the neutrino total cross sections to within 20-30%.

The simple ratios also suggest a simple physical interpretation in terms of the additive quark model.<sup>35</sup> For  $\Delta s = 0$  neutrino experiments the proton, as far as the integrals  $\int x f_i(x) dx$  are concerned, is composed of p- and n-type quarks. The total momentum carried by the p-quarks is approximately twice the momentum carried by the n-quarks.

With the beginning of neutrino experiments at NAL it is important to test Eq. (4-26). Such tests should be even more appealing in view of the fact that they do not depend on absolute fluxes, but only on relative  $\nu$  and  $\bar{\nu}$  fluxes.

8) Gluon Contribution: The momentum carried by the quarks is given by

$$\int x [f_p(x) + f_n(x) + f_\lambda(x) + f_{\bar{p}}(x) + f_{\bar{n}}(x) + f_{\bar{\lambda}}(x)] dx = 1 - \epsilon$$

If the quarks carry all the momentum<sup>24</sup>  $\epsilon = 0$ . Otherwise we have an indication that a fraction of the momentum is carried by constituents<sup>37</sup> which do not couple to the weak or electromagnetic currents. Available data provide a precise determination of  $\epsilon$

$$\epsilon = 1 + \frac{3}{2} \int \frac{F_2^{\nu p} + F_2^{\nu n}}{2} dx - 9 \int \frac{F_2^{\gamma p} + F_2^{\gamma n}}{2} dx$$

$$= 0.46 \pm 0.21$$

A sizable gluon contribution has been introduced to explain the momentum sum rule. Obviously, an independent confirmation of their presence or of their consequences is highly desirable.

Several important topics, like the sum rules,<sup>38,39</sup> are not being discussed, because the additional tests, made possible by the new data, are not very restrictive. For the sum rules, in particular, the integrals are of the form

$$\int [F_2^{\nu n}(x) - F_2^{\nu p}(x)] \frac{dx}{x} = 2 \cos^2 \theta_c \quad (\text{Adler Sum Rule})$$

$$\int [F_3^{\nu p} + F_3^{\nu n}] dx = -6 \quad (\text{Gross-Llewellyn-Smith})$$

and large contributions arise from small values of  $x$ .

## APPLICATIONS

One of the most pleasant aspects of this field is the many implications that it has for other problems of high energy physics. In 1960 Lee and Yang<sup>40</sup> compiled a list of unresolved problems of weak interactions; shown in Table 2. In the intervening years, a good deal of research has gone in resolving these problems. The question of the two neutrinos has been answered satisfactorily by the discovery of two neutrinos<sup>41</sup>. Here I would like to discuss some of the progress made concerning several of the other questions:

- (1) Neutral Currents
- (2) Intermediate Vector Bosons
- (3) Heavy Leptons

It is of interest to consider not only the best limits available, but also the prospects of improvement, opening up with the operation of new facilities.

### NEUTRAL CURRENTS

The revived interest on neutral currents arose from the possibility of constructing a renormalizable theory of weak (and electromagnetic) interactions.<sup>42</sup> Several models have been proposed which can achieve this goal at the expense of introducing neutral currents. Originally, the theories were concerned with leptonic interactions. Subsequently, they were generalized to account, by virtue of universality, for semileptonic reactions. We review here the present experimental bounds together with the corresponding theoretical predictions.

Leptonic Interactions. There are six leptonic processes, which involve neutrino beams incident on atomic electrons. The relevant Feynman diagrams are shown in Fig. 9. The first two reactions involve only neutral currents. Reactions 3-4 involve both neutral and charged currents. The last two reactions proceed only through the charged current of the conventional (V-A) theory. Their observation will provide additional confirmation of the theory. To my knowledge, there are no measurements or bounds for reactions 5 and 6 and we shall not discuss them any further.

A prototype of models with neutral currents is Weinberg's model<sup>43</sup> where the effective part of the Lagrangian pertinent

to leptonic reactions is

$$\mathcal{L}_L = \frac{G}{\sqrt{2}} \{ \bar{\nu} \gamma_\mu (1 + \gamma_5) \nu \quad \bar{e} \gamma^\mu (g_V + g_A \gamma_5) e \} \quad (5-1)$$

The effect of the neutral current is to change the values of  $g_V$  and  $g_A$  from those of (V-A)-theory to the ones shown in Table 3. The differential cross section<sup>44</sup> per unit energy of the recoil electron has the form

$$\frac{d\sigma}{dE} = \frac{G^2 m}{2\pi} \left[ (g_V + g_A)^2 + (g_V - g_A)^2 \left(1 - \frac{E}{E_\nu}\right)^2 + \frac{mE}{E_\nu^2} (g_A^2 - g_V^2) \right] \quad (5-2)$$

where  $E_\nu$  and  $E$  are the laboratory energies of the incident neutrino and recoiling electron,  $m$  is the electron mass.

Searches for the processes  $\nu_\mu e^- \rightarrow \nu_\mu e^-$  and  $\bar{\nu}_\mu e^- \rightarrow \bar{\nu}_\mu e^-$  were made in the Gargamelle experiment<sup>1,5</sup> and limits on the cross sections were set

$$\sigma(\nu_\mu e^- \rightarrow \nu_\mu e^-) \leq 0.7 \times 10^{-41} E_\nu \text{ cm}^2 \quad (5-3)$$

$$\sigma(\bar{\nu}_\mu e^- \rightarrow \bar{\nu}_\mu e^-) < 1.0 \times 10^{-41} E_\nu \text{ cm}^2 \quad (5-4)$$

Comparison with the Weinberg model provides the upper bound

$$\sin^2 \theta_W \leq 0.6$$

In a different experiment Gurr, Reines and Sobel<sup>45</sup> use a  $\bar{\nu}_e$ -beam from a nuclear reactor and search for the reaction  $\bar{\nu}_e e^- \rightarrow \bar{\nu}_e e^-$ . They observe only a small region of the phase space. When their results are translated into total cross sections they imply

$$\frac{\sigma(\bar{\nu}_e e^- \rightarrow \bar{\nu}_e e^-)_{\text{exp}}}{\sigma(\bar{\nu}_e e^- \rightarrow \bar{\nu}_e e^-)_{V-A}} \leq 3 \quad \begin{matrix} \text{(to better than} \\ \text{90\% c. l.)} \end{matrix} \quad (5-5)$$

Chen and Lee<sup>46</sup> analyzed this experiment in terms of the

Weinberg model and obtained the bound

$$\sin^2 \theta_W \leq .40 \quad (5-6)$$

An independent analysis by Baltay<sup>47</sup> confirms this value.

Semileptonic Interactions: The term of the effective Lagrangian relevant for semileptonic interactions has the form:

$$\mathcal{L}_{SM} = \frac{G}{\sqrt{2}} \{ \bar{\psi} \gamma^\alpha (1 + \gamma_5) \nu (J_\alpha^1 + i J_\alpha^2) + \text{h.c.} + \bar{\nu} \gamma^\alpha (1 + \gamma_5) \nu J_\alpha^{(0)} \} \quad (5-7)$$

with the hadronic neutral current given by

$$\begin{aligned} J_\alpha^{(0)} &= J_\alpha^3 + y J_\alpha^{\text{em}} + z J_\alpha^S \\ &= A_\alpha^3 + (1+y) V_\alpha^3 + J_\alpha^{'S} \end{aligned} \quad (5-8)$$

where

$J_\alpha^3$  is the third component of isospin for the usual weak current

$J_\alpha^{\text{em}}$  is the electromagnetic current and

$J_\alpha^S$  is an isoscalar current

The parameters  $y$  and  $z$  in some prototype models are

	GIM 48	Weinberg 49	-
$y$	$-2 \sin^2 \theta_W$	$-2 \sin^2 \theta_W$	
$z$	arbitrary	0	

Parameters of the same functional form also occur in models III and V,

described by Bjorken and Llewellyn-Smith<sup>50</sup>. In order to bound the parameter  $\sin^2 \theta_W$ , we appeal to universality and argue that it is the same parameter which occurs in purely leptonic reactions. The bound (5-6) from the Gurr, Reines and Sobel experiment<sup>45</sup> is, at the moment, the most restrictive and will be used in the subsequent numerical estimates.

Two important differences in the hadronic neutral current are the presence of an isoscalar component and the different admixture of vector and axial currents. Algebraic techniques have been developed, to account for these differences and bound the semileptonic cross sections from below. I mention three such theorems<sup>51</sup> and then return to the comparison between theory and experiment.

Theorem A: 1) In the effective Lagrangian (5-7), consider the ratios

$$R \equiv \frac{\frac{1}{2}[\sigma(\nu p \rightarrow \nu x_1) + \sigma(\nu n \rightarrow \nu x_2)]}{\frac{1}{2}[\sigma(\nu p \rightarrow \mu^- x_3) + \sigma(\nu n \rightarrow \mu^- x_4)]} \equiv \frac{\sigma_0}{\sigma_-} \quad (5-9)$$

where the  $x_i$ 's may refer either to all final states or a particular subset. The only requirement on the  $x_i$ 's is that we sum over all possible charge states of the final particles for each of the reactions

2) Define

$$V_{em} = \frac{G^2}{\pi} \int \frac{Q^4}{(4\pi\alpha^2)} \left\{ \frac{d\sigma(ep \rightarrow ex_1)}{dQ^2 dv d\Gamma} + \frac{d\sigma(en \rightarrow ex_2)}{dQ^2 dv d\Gamma} \right\} dQ^2 dv \quad (5-10)$$

where  $d\Gamma$  is a hadronic phase factor, defined by the subset of final state hadrons occurring in (5-9). Then

$$R \geq \frac{1}{2} \{1 - (1-x) \left(\frac{V_{em}}{\sigma_-}\right)^{1/2}\}^2 \quad (5-11)$$

where  $x = 1 + y = 1 - 2 \sin^2 \theta_W$ .

Data from antineutrino experiments is also very useful as it is indicated by the following two theorems.

Theorem B: Define

$$\bar{R} = \frac{\frac{1}{2}[\sigma(\bar{\nu}p \rightarrow \bar{\nu}x_1) + \sigma(\bar{\nu}n \rightarrow \bar{\nu}x_2)]}{\frac{1}{2}[\sigma(\bar{\nu}p \rightarrow \mu^+x_3) + \sigma(\bar{\nu}n \rightarrow \mu^+x_4)]} \equiv \frac{\bar{\sigma}_0}{\sigma_+} \quad (5-12)$$

where the  $x_i$ 's have similar meanings to those occurring in equation (5-9).

$$\text{Then} \quad \frac{1}{2} x = \frac{\sigma_0 - \bar{\sigma}_0}{\sigma_- - \sigma_+} \quad (5-13)$$

Theorem C: If it is known experimentally that the ratio

$$\frac{\sigma_-}{\sigma_+} \leq B$$

$$\text{then} \quad R \geq \frac{1}{2} \left\{ x + (1-x) \frac{B+1}{2B} - (1-x^2) \frac{V_{em}}{\sigma_-} \right\} \quad (5-14)$$

Depending on the experimental situation either of equations (5-11) or (5-14) can be more restrictive and one should check both of them explicitly.

We now compare the theoretical predictions with the experimental bounds.

(i) Total Cross Sections: Pais and Treiman<sup>52</sup>, assuming scaling and the parton relation given in equation (3-6), derived

$$R \equiv \frac{\sigma(\nu p \rightarrow \nu x_1) + \sigma(\nu n \rightarrow \nu x_2)}{\sigma(\nu p \rightarrow \mu^- x_3) + \sigma(\nu n \rightarrow \mu^- x_4)} \geq \frac{1}{6} (1+x+x^2) \quad (5-15)$$

Subsequently Paschos and Wolfenstein<sup>51</sup> eliminated the parton assumption by appealing to the experimental results: (a) electroproduction data scale (scaling for neutrinos is not assumed) and (b) the ratio in Eq.(2-14);

then using theorem C obtained essentially the same bound. Both of these results refer to isoscalar nuclei. But since most of the contribution to the cross section comes from large values of  $Q^2$  and comparable values of  $\nu$  it is safe to assume that the process is incoherent. Then defining  $R(Z,A)$  in analogy to the  $R$  occurring in (5-15), but on a nucleus with  $Z$  protons and  $(A-Z)$  neutrons we obtain

$$R(Z,A) \geq \frac{Z}{A-Z} R \geq 0.17 \quad (5-16)$$

The corresponding experimental bound on  $R$  is

$$R(Z,A) \leq 0.2 \quad (90\% \text{ c.l.}) \quad (5-17)$$

(ii) Single  $\pi^0$  production:

There are two experimental upper bounds for the ratio

$$R_1 = \frac{\sigma(\nu + p \rightarrow \nu p \pi^0) + \sigma(\nu + n \rightarrow \nu n \pi^0)}{\sigma(\nu + n \rightarrow \nu p \pi^0 \mu^-)} \leq .14$$

BNL-Columbia<sup>53</sup>  
(W. Lee)

(5-18)

$$\leq .21$$

Gargamelle<sup>54</sup>

It is important to notice that protons and neutrons in the target are not free but they are bound in nuclei. A bound obtained in the static model originally by Ben Lee<sup>55</sup> has been reanalyzed recently by Albright, Lee, Wolfenstein and Paschos<sup>56</sup>. In the new analysis one considers the scattering from an isospin zero nucleus and describes the final states in terms of

the isospin of the resulting nucleus and a pion. In this manner all final state interactions are included, except for electromagnetic effects. The resulting formula is

$$R_1 \geq \frac{1}{4} [(r-1)^{1/2} - 2 \sin^2 \theta_W \left( \frac{V_{e.m.}^{\circ}}{\sigma(\nu N \rightarrow \mu^- \pi^0 x_3)} \right)^{1/2}]^2 \quad (5-19)$$

where

$$r = \frac{\sigma(\nu N \rightarrow \pi^+ + \mu^- + x_1) + \sigma(\nu N \rightarrow \mu^- + \pi^- + x_2)}{\sigma(\nu N \rightarrow \mu^- \pi^0 x_3)} \quad (5-20)$$

For numerical estimates one must know the electroproduction of  $\pi^0$ 's in nuclei.

Data for the electroproduction of  $\pi^0$ 's in nuclei is not yet available and  $V_{em}^{\circ}$  was estimated making generous allowances for the uncertainties.<sup>56</sup> In addition we need the ratio  $r$ . I plotted in Fig. 10  $R_1$  as a function of  $r$ . The Gargamelle experiment<sup>54</sup> gives a value close to  $\sim 3$  and it does not rule out a neutral current. On the other hand the BNL-Columbia  $\nu$  experiment is a lower incident energy experiment and according to W. Lee<sup>57</sup> the ratio  $r$  is presumably larger than three. A value of  $r$  considerably larger than 3 would imply a significant disagreement between the Weinberg model and this experiment.

(iii) The Argonne group reported<sup>2</sup> an upper bound on a hydrogen target

$$R_3 = \frac{\sigma(\nu p \rightarrow \nu n \pi^+) + \sigma(\nu p \rightarrow \nu p \pi^0)}{\sigma(\nu p \rightarrow \mu^- \Delta^{++})} \leq 0.31 \quad (5-21)$$

$\leq 0.46$  Cundy et al.<sup>58</sup>  
(90% c.l.)

Using the same techniques<sup>56</sup> we obtain

$$R_3 \geq \frac{1}{3} \{1 - 2 \sin^2 \theta_W \left[ \frac{V_{e.m}(\Delta^+)}{2/3\sigma(\Delta^{++})} \right]^{1/2} \}^2 \quad (5-22)$$

$$\geq 0.10 \quad (\text{Th.})$$

This bound is true in both models and it does not depend on any additional assumptions, like isoscalar target or estimates for  $V_{e.m}(\Delta^+)$ . Data for  $V_{e.m}(\Delta^+)$  and  $\sigma(\Delta^{++})$  are available and have been used for the numerical calculation. The bounds of sections (i)-(iii) hold in the models of references 48-50.

(iv) The old CERN experiment<sup>58</sup> determined the ratio

$$R_4 \frac{\sigma(\nu p \rightarrow \nu n \pi^+)}{\sigma(\nu p \rightarrow \mu^- \Delta^{++})} \leq 0.16 \quad (90\% \text{ c.l.}) \quad (5-23)$$

The same methods have been used<sup>56</sup> to bound this ratio from below in the specific Weinberg model. The only assumption required is incoherence of the  $I = 3/2$  and  $I = 1/2$  amplitudes to obtain

$$R_4 \geq .03 \quad (\text{Th.}) \quad (5-24)$$

#### (v) Elastic Scattering

In the same experiment<sup>58</sup> an upper bound was also established for the ratio

$$R_5 = \frac{\sigma(\nu p \rightarrow \nu p)}{\sigma(\nu n \rightarrow \mu^- p)} \leq 0.24 \quad (90\% \text{ c.l.}) \quad (5-24)$$

Bounds have been obtained for this ratio by Weinberg.<sup>49</sup> In his work the elastic vector and axial form factors are related to the form factors of the processes

$e + p \rightarrow e + p$  and  $\nu + n \rightarrow \mu^- + p$ . In order to obtain some idea of the numerical values of the bounds terms of  $O(\frac{Q^2}{2M^2})$  or smaller were neglected, because for most of the events such ratios are indeed small. For  $\sin^2 \theta_W \leq .33$  he obtained

$$0.15 \leq R_5 \leq 0.25 \quad (5-25)$$

If one worries about the approximations, he can appeal to Schwarz's inequality and obtain

$$R_5 \geq \frac{1}{4} \{1 - 2 \sin^2 \theta_W [\frac{V_{em}}{\sigma(\nu n \rightarrow \mu^- p)}]^{1/2}\}^2 \quad (5-26)$$

where

$$V_{em} = \frac{G^2}{\pi} \int \frac{Q^4}{4\pi\alpha^2} \frac{d\sigma}{dQ^2} (e + p \rightarrow e + p) dQ^2 \quad (5-27)$$

$V_{em}$  is calculated using the electromagnetic form factors of the proton

$$V_{em} = 0.66 \times 10^{-38} \text{ cm}^2 \quad (5-28)$$

The neutrino cross section<sup>59</sup> is known

$$\sigma(\nu n \rightarrow \mu^- p) = 0.80 \times 10^{-38} \text{ cm}^2 \quad (5-29)$$

Thus we arrive at

$$R_5 \geq 0.02 \quad (5-30)$$

for the Weinberg angle given in (5-6).

In summary, Table 4 gives an overview of the present situation. The most striking feature is the proximity of the bounds. In my opinion, there is not a single process which convincingly eliminates the presence of neutral currents in

models of the Weinberg type. It seems, however, that the experiments have the capability for improving the bounds and more critical tests could be made in the near future.

### Neutral Currents in Colliding Beam Experiments

A neutral current could also contribute to the reaction

$$e^+ + e^- \rightarrow \mu^+ + \mu^-$$

and might be observable depending on its strength relative to the strength of the electromagnetic current, which dominates the reaction. This possibility is enhanced by the expectation that the circulating beams in  $e^+e^-$  colliding rings will have a large transverse polarization<sup>60</sup>, along or opposite the direction of the magnetic field. In certain angular regions the single photon exchange contribution is sharply decreased, providing the opportunity of observing neutral current effects or higher order electromagnetic effects. The conclusions of several studies<sup>61</sup> are: (a) the muon polarization arising from weak effects is enhanced by the polarization of the beams to a value of  $\sim 3\%$ . For a realistic experiment<sup>62</sup> one expects  $2L \times 10^{-31}$  counts/hour, where  $L$  is the storage ring luminosity in  $\text{cm}^{-2} \text{ sec}^{-1}$ , (b) The muon polarization arising from two photon exchange is minimal at the angular region where the weak polarization is maximal, (c) A more accessible signal is the asymmetry between  $(\theta, \phi)$  and  $(\pi - \theta, \phi)$  in the muon differential cross section. The asymmetry arising from weak effects is again a few percent resulting to counting rates comparable to those discussed above. Higher order electromagnetic corrections<sup>63</sup> give rise to comparable effects. In

order to distinguish between the two effects one needs high precision experiments.

### INTERMEDIATE VECTOR BOSONS -- HEAVY LEPTONS

The ideas discussed so far will be affected by the presence of either a heavy boson or of heavy leptons. The presence of a W-boson will change the linear rise of the cross section to a logarithmic rise<sup>8</sup>. Its presence will also be reflected in the mean muon energy<sup>14</sup>. It was shown in Eq. (3-10) that scaling and the present data require  $\langle E_\mu/E_\nu \rangle$  to be close to 1/2. Figure 11 shows the modification arising from the presence of a W-propagator. Deviations from a straight line become noticeable at  $S/M_W^2 \sim 1 - 2$ . Such a test is sensitive to a W-mass  $M_W \sim 1.15 \sqrt{ME_\nu}$ .

The presence of a heavy lepton<sup>64</sup> produces just the opposite effect. The process now proceeds through the steps

$$\begin{array}{c} \nu + p \rightarrow \ell^* + x \\ \quad \searrow \\ \quad \ell + Y \end{array}$$

In such a reaction  $\ell^*$  carries, in the mean, half of the neutrino energy. In the subsequent decay  $\ell$  carries only a fraction of  $\ell^*$ 's energy so that  $\langle E_\mu/E_\nu \rangle$  should be lower than 1/2.

### OTHER PROCESSES

Processes of the form

$$\begin{aligned} p + p &\rightarrow \mu^+ + \mu^- + \text{anything} \\ &\rightarrow \gamma + \gamma + \text{anything} \end{aligned}$$

have been analyzed in some kinematic regions in terms of parton-antiparton annihilation into leptons<sup>65</sup>. The neutrino cross sections indicate that the momentum carried by  $\bar{p}$  and  $\bar{n}$  quarks is small (Eq. 4-18). Consequently, if the processes arise from quark-antiquark annihilations there is a correlation of small values of  $x'$  for antiquarks<sup>66</sup> with sizable values of  $x$  for quarks. Such correlations will be reflected in the detailed phase-space distribution of the data.

It has been four years since the time when the scaling phenomenon became apparent in the SLAC-MIT experiments. In the short time since then we seem to have come a long way. Taking alone anyone of the comparisons, which I discussed, it does not present convincing evidence in favor of these ideas. But taking them all together it seems as if the pieces of the puzzle fall together and a Thomson picture of the proton may be emerging at energies a billion times larger. To paraphrase a quotation from J. J. Thomson<sup>67</sup> "These experiments and theoretical ideas have opened up new fields of investigation, which we hope with confidence, that they will throw much light on two fundamental questions: What is the structure of hadrons and the nature of weak interactions?"

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## REFERENCES AND FOOTNOTES

1. V. Brisson XVI International Conference on High-Energy Physics (to be referred as XVI ICHEP) Chicago-Batavia 2, 195 (72).  
Ph. Heusse XVI ICHEP Chicago-Batavia 2, 206, 1972.  
P. Musset Invited Talk at this Meeting.  
Cross sections from the old propane experiment are given by I. Budagov et al. Phys. Lett. 30B, 364 (1969).
2. Y. Cho XVI ICHEP Chicago-Batavia 2, 195 (72);  
P. Schreiner XVI ICHEP Chicago-Batavia 2, 200 (72)  
and this Meeting.
3. C. H. Llewellyn-Smith, Physics Reports 3C, 263 (72).
4. A. Pais, Annals of Physics 63, 361 (1971).
5. D. H. Perkins, Report presented at the XVI ICHEP Chicago-Batavia 1972.
6. T. D. Lee and C. N. Yang, Phys. Rev. 126, 2239 (1962).
7. F. J. Gilman, Phys. Rev. 167, 1365 (1968).
8. J. D. Bjorken and E. A. Paschos, Phys. Rev. D1, 3151 (1970).
9. J. D. Bjorken, Phys. Rev. 179, 1547 (1969).
10. G. Miller et al. Phys. Rev. D5, 528 (1972); A. Bodek et al. XVI ICHEP, Chicago-Batavia 1972; A. Bodek (MIT thesis), M.I.T. Report No. COO-3069-116 (1972).
11. See the NAL proposal for E26.
12. M. Froissart, Phys. Rev. 123, 1053 (1961).  
Arguments based on a limited number of partial waves do not apply either because the number of partial waves in the current hadron system is unlimited. See also V. I. Zakharov, XVI ICHEP Chicago-Batavia 2, 275, (1972).

13. I. Pomeranchuk, Zh. Eksperim. i Theor. Fiz 34, 725 (58);  
[English trans. Soviet Phys.-JETP, 7, 499 (58)].
14. E. A. Paschos and V. I. Zakharov, NAL Preprint,  
NAL-THY-100 (to be published in Phys. Rev.).
15. C. G. Callan and D. J. Gross, Phys. Rev. Lett. 22, 156  
(1969).
16. P. Musset at this Meeting and private communication.
17. G. Myatt and D. H. Perkins, Phys. Lett. 34B, 542 (1971).
18. R. P. Feynman, Phys. Rev. Lett. 23, 1415 (1969) and in  
the Proceedings of the Third Topical Conference on  
High Energy Collisions, Stony Brook (N.Y.) (1969).
19. J. D. Bjorken and E. A. Paschos Phys. Rev. 185, 1975  
(1969).
20. S. Drell and T. M. Yan Phys. Rev. D1, 2402 (1970);  
Annals of Physics 66, 555 (1971) and references therein.
21. D. Gross and C. H. Llewellyn-Smith Nuclear Phys. B14,  
337, (1969).
22. J. Kuti and V. F. Weisskopf, Phys. Rev. D4, 3418 (1971).
23. P. Landshoff and J. C. Polkinghorne, Nucl. Phys. B28,  
240 (71).
24. H. Fritzsch and M. Gell-Mann, in Proceedings of the  
Coral-Gables Conference on Fundamental Interactions at High  
Energy (1971), and in Proceedings of the International  
Conference on Duality and Symmetry in Hadron Physics,  
Tel-Aviv (1971).

25. J. M. Cornwall and R. Jackiw, Phys. Rev. D4, 367 (1971);  
 D. J. Gross and S. B. Treiman, Phys. Rev. D4, 1059 (1971);  
 L. Brown, Boulder Lectures, 1969;  
 R. A. Brandt and G. Perparata, Nucl. Phys. B27, 541 (1971)  
 and references therein;  
 Y. Frishman, Phys. Rev. Letters 25, 966 (1970);  
 R. Jackiw, R. P. Van Royen and G. West, Phys. Rev. D2,  
 2473 (1970);  
 H. Leutwyler and J. Stern, Nucl. Phys. B20, 77 (1970).  
 For a recent review see Y. Frishman, XVI ICHEP Chicago-  
 Batavia 1972.
26. R. P. Feynman Proc. of the 1972 Europhysics Neutrino  
 Conference, Balatonfured, Hungary; Photon Hadron  
 Interactions, W. A. Benjamin, N.Y. (1972), Appendix B  
 in the book is attributed to J. D. Bjorken.
27. H. Lipkin, private communication and to be published.
28. C. H. Llewellyn-Smith, Nucl. Phys. B17, 277 (1970).
29. D. Cline and E. A. Paschos, University of Wisconsin  
 preprint (1973).
30. O. Nachtmann, J. Physique 32, 99 (1971); Nucl. Phys.  
B38, 397 (1972); also Phys. Rev. D5, 686 (1972);  
 D. P. Majumdar, *ibid.* 3, 2869 (1971). C. Callan et al.  
 Phys. Rev. D6, 387 (1972).
31. A Bodek, ref. 10.
32. E. A. Paschos, XVI ICHEP - Chicago-Batavia 2, 166, 1972.
33. Symmetry relations have been studied with Han-Nambu  
 quarks (Phys. Rev. 139, B1006 (1965)). Since charmed  
 states have not been observed one must demand that

all  $\Delta C \neq 0$  transitions vanish, in which case the predictions are identical to the Gell-Mann-Zweig quarks (H. Lipkin, Phys. Rev. Lett. 28, 63 (1972)).

Models with different predictions must assume either that charmed states have already been produced and escaped detection or that the quarks recombine on the way out to form only  $C = 0$  states.

See: R. Budny, T. H. Chang and D. K. Choudhury  
Nucl. Phys. B44, 618 (1972)

D. H. Perkins, ref. 5;

M. Koca and M. S. K. Razmi, ICTP - preprint; IC/72/132.

It has also been argued that the symmetry relations follow from assumptions common in hadron scattering  
S. Pallua and B. Renner, Phys. Letters 38B, 105 (72);  
H. J. Lipkin and E. A. Paschos, Phys. Rev. Lett. 29, 525 (72).

M. Chaichian, S. Kitakado, S. Pallua and Y. Zarmi  
CERN - preprint THY-1626 and references therein.

34. H. A. Kendall, Proceedings of the 1971 International Symposium on Electron and Photon Interactions at High Energies, Ed. N. B. Mistry, (Cornell University).  
After the APS Meeting, I received Bodek's thesis which indicates that a more precise estimate of the ratio is now possible. From G. Miller et al. (ref. 10)

$$\int_{0.05}^1 F_2^{\gamma P}(x) dx = 0.172 \pm 0.009$$

and from Bodek's thesis (ref. 10)

$$\int_{0.05}^1 F_2^{\gamma n}(x) dx = 0.127 \pm 0.011$$

leading to

$$\frac{\int F_2^{\gamma n}(x) dx}{\int F_2^{\gamma p}(x) dx} = 0.738 \pm 0.042 = 0.74 \pm \xi$$

The error in the last ratio is very conservative, since it was assumed that the errors are uncorrelated. Explicit information on the error matrix could provide a more accurate determination of the ratio. Eq. (4-22) now becomes

$$0.52 - 1.69 \xi \leq \frac{\int x f_n(x) dx}{\int x f_p(x) dx} \leq 0.60 + 1.41 \xi$$

and the subsequent relations (4-25) should be changed accordingly. I wish to thank Professor V. Barger for helpful comments.

35. E. M. Levin and L. L. Frankfurt, AhETF Pis. Red. 2, 105 (1965) [English transl. JETP Letters 2, 65 (1965)].

H. J. Lipkin and F. Scheck, Phys. Rev. Lett. 2, 61 (1966).

In analyzing the neutrino data it must be remembered that present experiments are at rather low energies with  $\langle Q^2 \rangle \sim 1-2 \left( \frac{\text{GeV}}{c} \right)^2$  (Eq. 3-13) and may not reflect the asymptotic behavior. The hope is that the qualitative features will persist at higher energies where the same interpretation will again be possible. Extension of scaling to lower values of  $Q^2$  has been studied by

- E. D. Bloom and F. J. Gilman, Phys. Rev. Lett. 25, 1140 (72).
- V. Rittenberg and H. R. Rubinstein, Phys. Lett. 35B, 50 (1971).
36. M. Gourdin, Nuclear Physics B29, 601 (1971) and Orsay preprint PAR-LPTHE 10 (1972).
37. C. H. Llewellyn-Smith, Phys. Rev. D4, 2392 (1971).
38. S. Adler, Phys. Rev. 143, 1144 (1966).  
J. D. Bjorken, Phys. Rev. 163, 1767 (1967).  
D. Gross and C. H. Llewellyn-Smith, reference 21.  
J. D. Bjorken, Phys. Rev. D1, 1376 (1970).
39. The saturation of the same rules in the deep inelastic region attracted considerable attention H. Pagels, Phys. Rev. D3, 1217 (1971).  
J. D. Bjorken and S. F. Tuan, Comments on Nuclear and Particle Physics (1969); J. J. Sakurai, H. B. Thacker and S. F. Tuan, Nucl. Phys. B (in press);  
E. A. Paschos, reference 32;  
S. F. Tuan, Institute for Advanced Study Preprint (1972);  
O. Nachtmann, Institute for Advanced Studies Preprint (1973).
40. T. D. Lee and C. N. Yang, Phys. Rev. Lett. 4, 307 (1960).  
This list has been updated periodically.  
C. H. Llewellyn-Smith, CERN Summer Study (1972).
41. G. Danby, J. M. Gaillard, K. Goulianos, L. M. Lederman, N. Mistry, M. Schwartz and J. Steinberger, Phys. Rev. Lett. 9, 36 (1962).

42. For a recent summary see:  
B. W. Lee, "Perspectives on Theory of Weak Interactions".  
Talk at the XVI ICHEP - Chicago-Batavia 1972.
43. S. Weinberg, Phys. Rev. Letters 19, 1264 (1967);  
Phys. Rev. D5, 1412 (1972). See also A. Salam,  
Elementary Particle Theory, edited by N. Svartholm  
(Almquist and Forlag A. B., Stockholm, 1968).
44. H. H. Chen and B. W. Lee, Phys. Rev. D5, 1874 (1972);  
G. 't Hooft, Phys. Letters 37B, 197 (1971).
45. H. S. Gurr, F. Reines and H. W. Sobel, Phys. Rev. Lett.  
28, 1406 (1972).
46. H. H. Chen and B. W. Lee, reference 44.
47. C. Baltay, Proceedings of the 1972 Europhysics Neutrino  
Conference, Balatonfured, Hungary.
48. S. L. Glashow, J. Iliopoulos, L. Maiani, Phys. Rev. D2,  
1285 (1970). This paper is referred to as GIM in the text.
49. S. Weinberg D5, 1412 (1972).
50. J. D. Bjorken and C. H. Llewellyn-Smith Phys. Rev. D7,  
887 (1973).
51. E. A. Paschos and L. Wolfenstein, Phys. Rev. D7, 91  
(1973).
52. A. Pais and S. Treiman, Phys. Rev. D6, 2700 (1972).
53. W. Lee, Phys. Letters 40B, 423 (1972).
54. This bound is larger than the one presented at the  
Chicago-Batavia Conference, Musset at this Meeting.
55. B. W. Lee, Phys. Letters 40B, 420 (1972).
56. C. H. Albright, B. W. Lee, E. A. Paschos and L. Wolfenstein  
NAL - preprint THY-86B to be published in Phys. Rev.

57. W. Lee, private communication.
58. D. C. Cundy, G. Myatt, F. A. Nezrick, J. B. M. Pattison, D. H. Perkins, C. A. Ramm, W. Venus, and H. W. Wachsmuth, Phys. Letters 31B, 478 (1970).
59. I. Budagov et al. Nuovo Cim. Lett. 2, 689 (1969).
60. J. Le Duff, P. C. Marin, P. Petroff and E. Sommer, Proc. of the Int'l. Symp. on Electron and Photon Interaction at High Energies, Cornell University, Ithaca, N. Y. (1971).
61. A. Love, Nuovo Cimento Letters 5, 113 (1972).  
J. Godine and A. Hankey, Phys. Rev. (to be published).  
V. K. Cung, A. K. Mann and E. A. Paschos, Phys. Letters 41B, 355 (1972).  
G. V. Grigoryan and A. Khoze, (Yerevan Phys. Inst. Preprint) Journal of Nucl. Phys. 5, 1078 (1972).
62. D. B. Cline, A. K. Mann, D. Reeder, SLAC-proposal unpublished.
63. I. B. Khriplovich, Novosibirsk preprint, submitted to the Chicago-Batavia Conference 1972 (to be published).  
R. W. Brown, V. K. Cung, K. O. Mikaelian and E. A. Paschos, Phys. Lett. 43B, 403 (1973);  
D. A. Dicus, Rochester preprint (1973).
64. For a recent survey of heavy lepton effects see:  
M. Perl. SLAC preprint SLAC-PUB-1062 (72).
65. S. D. Drell and T. M. Yan, reference 20;  
J. Kuti and V. Weisskopf, reference 22;  
S. Berman, J. D. Bjorken, J. Kogut, Phys. Rev. D4, 3388 (1971).

66. The existing data do not restrict the momentum carried by the  $\lambda$ ,  $\bar{\lambda}$  quarks, so that the argument could (although not expected) be affected by  $\lambda$ - $\bar{\lambda}$  annihilations.
67. J. J. Thomson, Beyond the Electron, Cambridge University Press (1928), p. 34.

## TABLE CAPTIONS

1. Summary of quantities determined by the electromagnetic and weak data. The electromagnetic integrals have been multiplied by 4 as indicated in Eq. (4-8).
2. Unresolved problems of weak interactions.
3. Effective couplings in the Weinberg Model.
4. Neutral Current Effects. A comparison between the experimental upper bounds with the theoretical lower bounds.

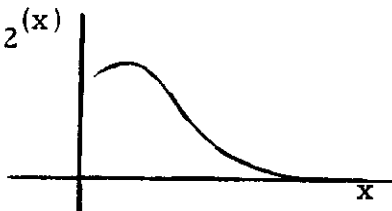
FEATURE	ELECTRONS	NEUTRINOS
Scaling	$F_2(x)$ 	$\sigma^{\nu} \rightarrow C \cdot E_{\nu}$
Spin 1/2	$\sigma_S / \sigma_T = 0.14 \pm 0.10$	$\frac{\langle S \rangle}{\langle L \rangle} \leq \frac{1}{2} \epsilon \approx 0.06$
Momentum Carried by Antiparticles	- - - -	$\sigma_R \approx 0 \rightarrow \frac{\sigma_{\bar{\nu}}}{\sigma_{\nu}} \approx \frac{1}{3}$
$\int F_2(x) dx$	$0.52 \pm 0.08$	$0.47 \pm 0.07$
$\int x F_2(x) dx$	$\sim 0.12$	$\sim 0.11$

TABLE 1

Questions raised by Lee and Yang [ Phys. Rev. Letters 4, 307 (1960) ]	Experimental answers from $\nu$ experiments
1) $\nu_{\mu} = \nu_e$ ?	$\nu_{\mu} \neq \nu_e$
2) Lepton conservations $\nu \rightarrow L^+$ and $\rightarrow L^-$ ?	See ref. 64
3) Neutral Currents ?	See pg. 20-30
4) "Locality" (vector nature of weak interactions)	- - -
5) Universality between $\nu_{\mu}$ and $\nu_e, \mu$ and $e$ ?	- - -
6) Charge symmetry ?	- - -
7) CVC; isotriplet current ?	- - -
8) $W$ ?	$M_W > 1.8 \text{ GeV}$
9) What happens at high energy ( $E_{\nu} \rightarrow$ "unitarity limit") ?	- - -

TABLE 2

Leptonic Couplings in the Weinberg Theory

Reaction	Weinberg		V-A Theory	
	$g_V$	$g_A$	$g_V$	$g_A$
$\nu_\mu + e^- \rightarrow e^- + \nu_\mu$	$-\frac{1}{2} + 2 \sin^2 \theta_W$	$-\frac{1}{2}$	0	0
$\bar{\nu}_\mu + e^- \rightarrow e^- + \bar{\nu}_\mu$	$-\frac{1}{2} + 2 \sin^2 \theta_W$	$+\frac{1}{2}$	0	0
$\nu_e + e^- \rightarrow e^- + \nu_e$	$\frac{1}{2} + 2 \sin^2 \theta_W$	$+\frac{1}{2}$	1	1
$\bar{\nu}_e + e^- \rightarrow e^- + \bar{\nu}_e$	$\frac{1}{2} + 2 \sin^2 \theta_W$	$-\frac{1}{2}$	1	-1

TABLE 3

RATIO	EXPERIMENT (90% C.L.)	THEORY
$\frac{\sigma(\nu N \rightarrow \nu x^0)}{\sigma(\nu N \rightarrow \mu^- x^+)}$	$\leq 0.2$	$\geq .17$
$\frac{\sigma(\nu p \rightarrow \nu p \pi^0) + \sigma(\nu n \rightarrow \nu n \pi^0)}{2\sigma(\nu n \rightarrow \mu^- p \pi^0)}$	$\leq .14$ W. Lee $\leq .21$ Gargamelle	$\geq 0.44$ to $0.07$
$\frac{\sigma(\nu p \rightarrow \nu n \pi^+) + \sigma(\nu p \rightarrow \nu p \pi^0)}{\sigma(\nu p \rightarrow \mu^- \Delta^{++})}$	$\leq .46$ Cundy et al. 58 $\leq .31$ ANL	$\geq 0.10$
$\frac{\sigma(\nu p \rightarrow \nu p)}{\sigma(\nu n \rightarrow \mu^- p)}$	$\leq .24$	$.15 \leq R \leq .25$
$\frac{\sigma(\nu p \rightarrow \nu n \pi^+)}{\sigma(\nu p \rightarrow \mu^- \Delta^{++})}$	$\leq .16$	$\geq 0.03$

TABLE 4

## FIGURE CAPTIONS

1. Kinematics of inelastic neutrino nucleon scattering.
2. Neutrino and antineutrino total cross sections as functions of the incident energy (ref. 1,5).
3. Ratio of the antineutrino to neutrino total cross sections as a function of the incident energy (ref. 1,5).
4. Kinematics of the "parton-picture".
5. Helicity conservation in the current-parton system.
6. Born diagram contributions to  $W_2(Q^2, \nu)$ .
7. Lower bound (open circles) for the ratio  $F_2^{\nu n}/F_2^{\nu p}$  implied by the electroproduction data (solid dots with errors). The electroproduction data are taken from A. Bodek et al. ref. 10.
8. "Parton-picture" at  $x \approx 1.0$ .
9. Born diagrams for processes which involve neutrino (anti-neutrino) beams incident on atomic electrons.
10. The W. Lee ratio as a function of  $r$ . Horizontal lines show the experimental upper bounds.
11. The mean energy of the muon in the presence of an intermediate vector boson as a function of  $S/M_W^2$ .

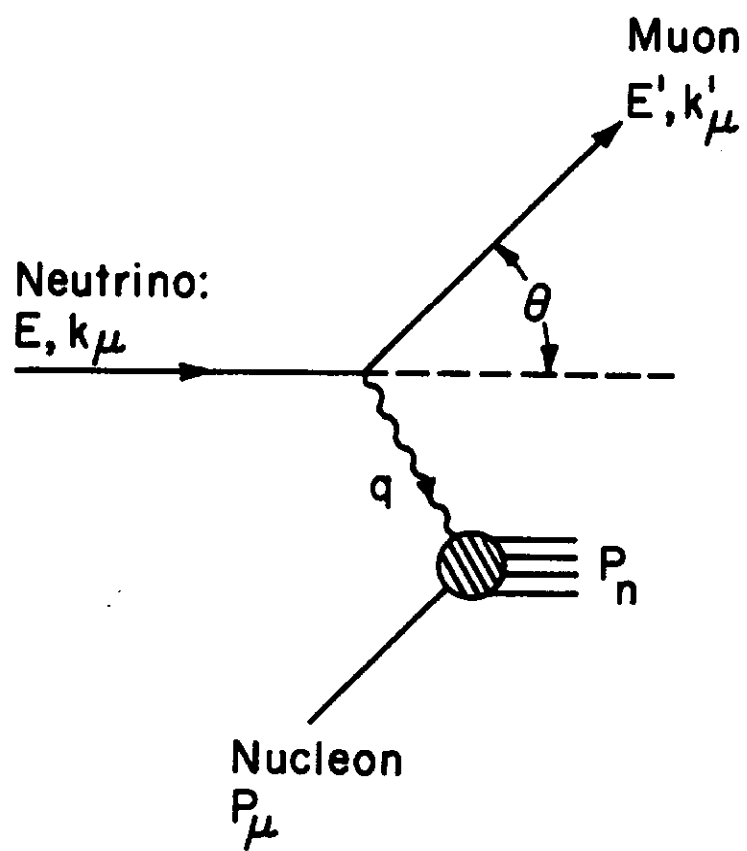


Figure 1

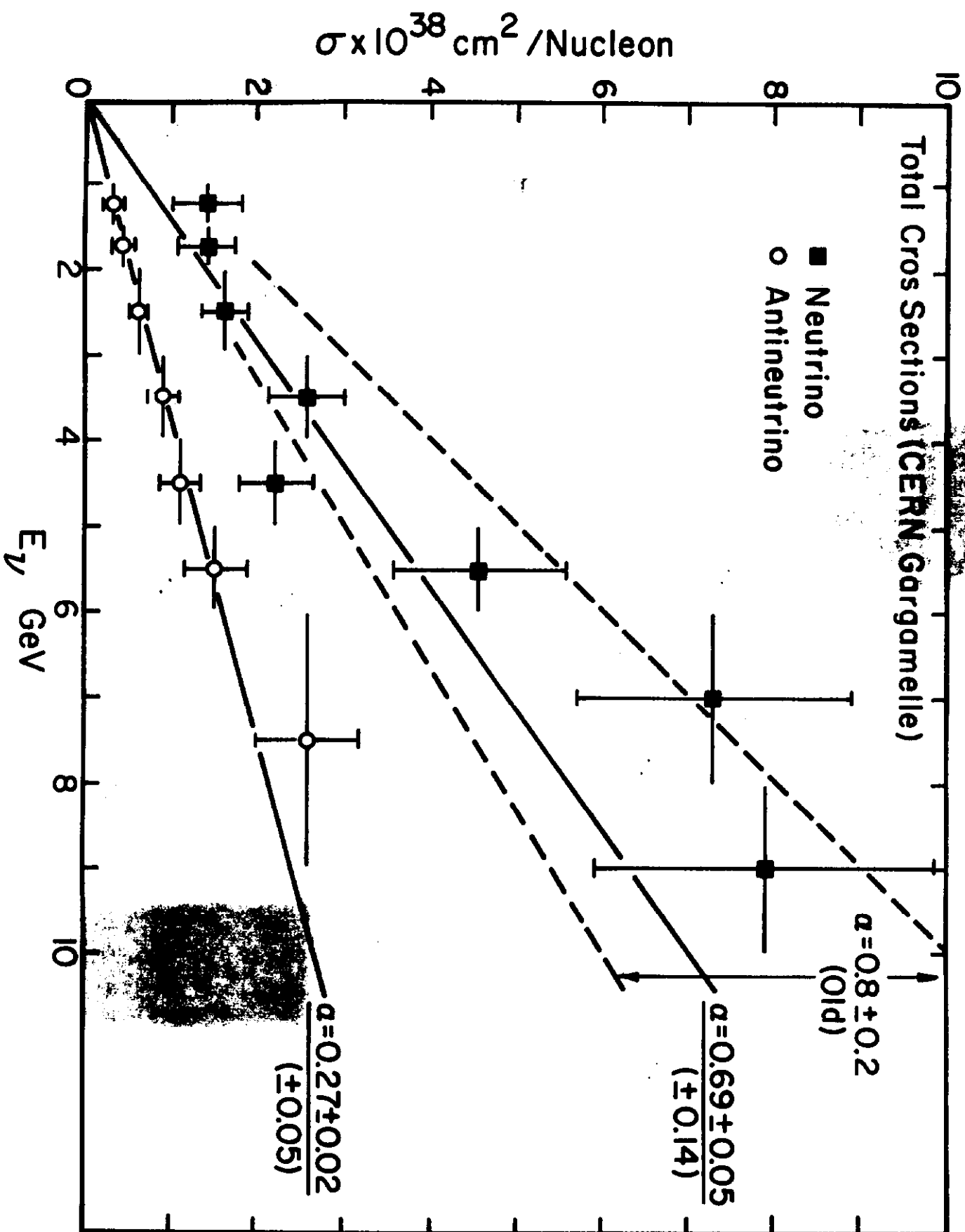


Figure 2

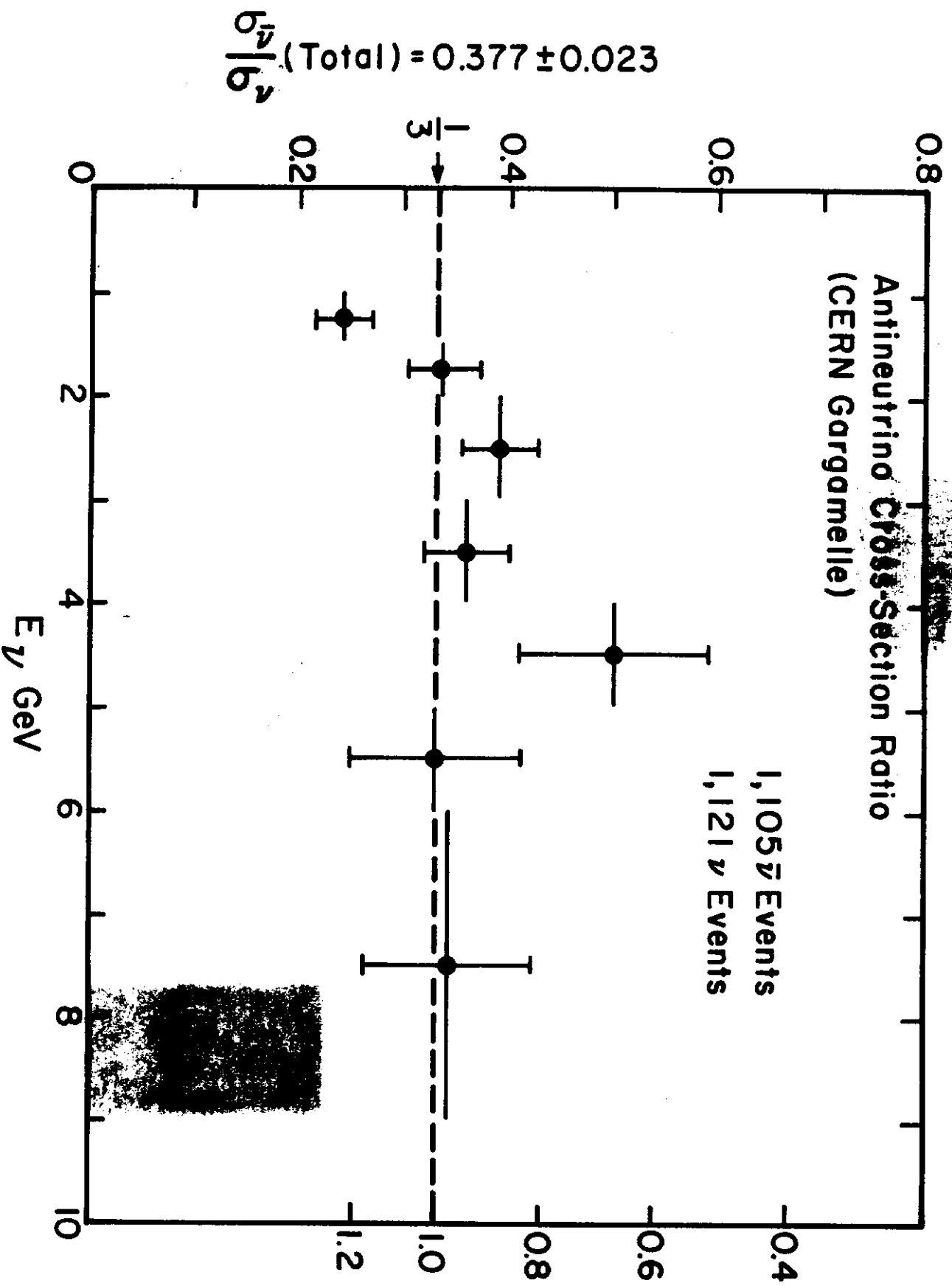


Figure 3

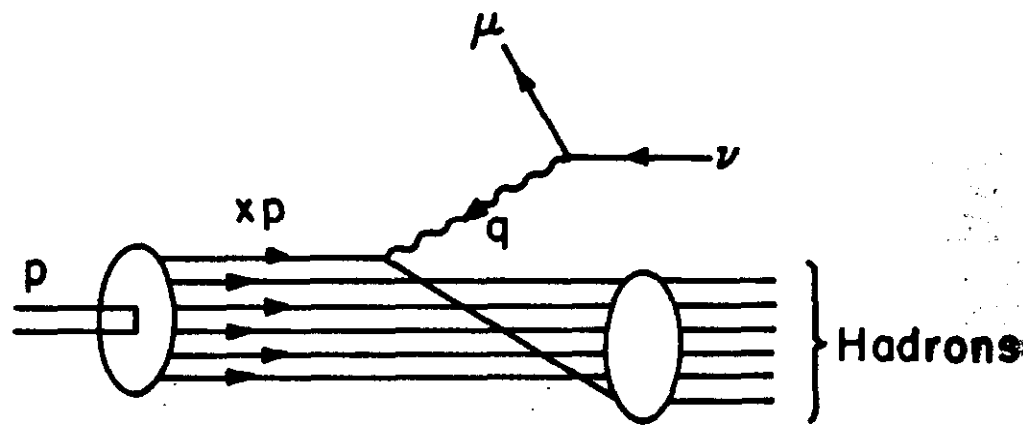


Figure 4

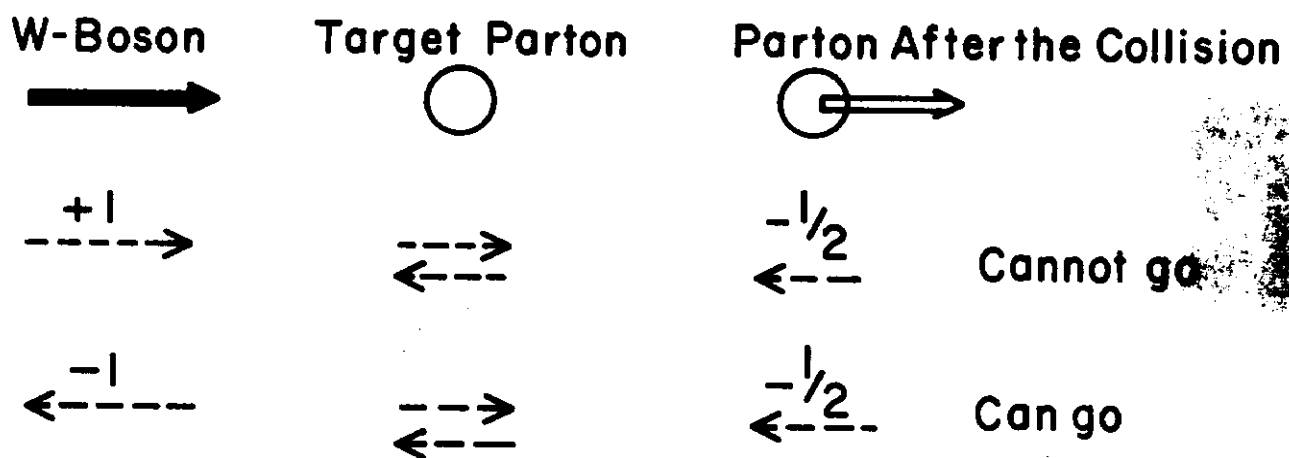
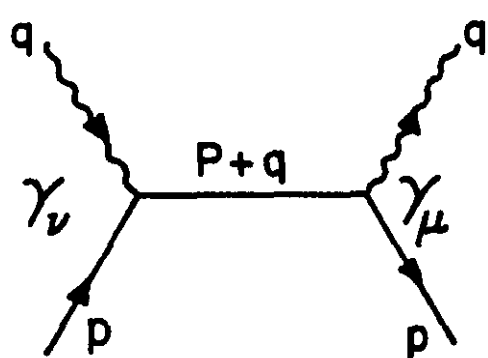
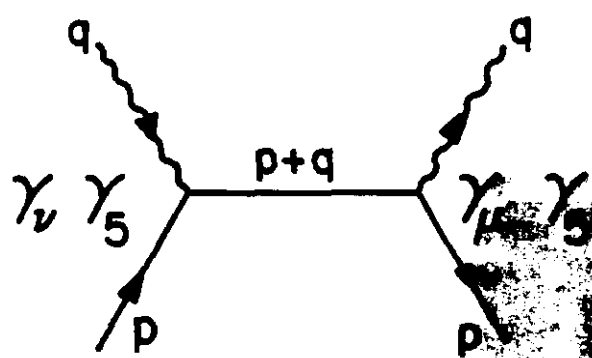


Figure 5



(V)



(A)

Figure 6

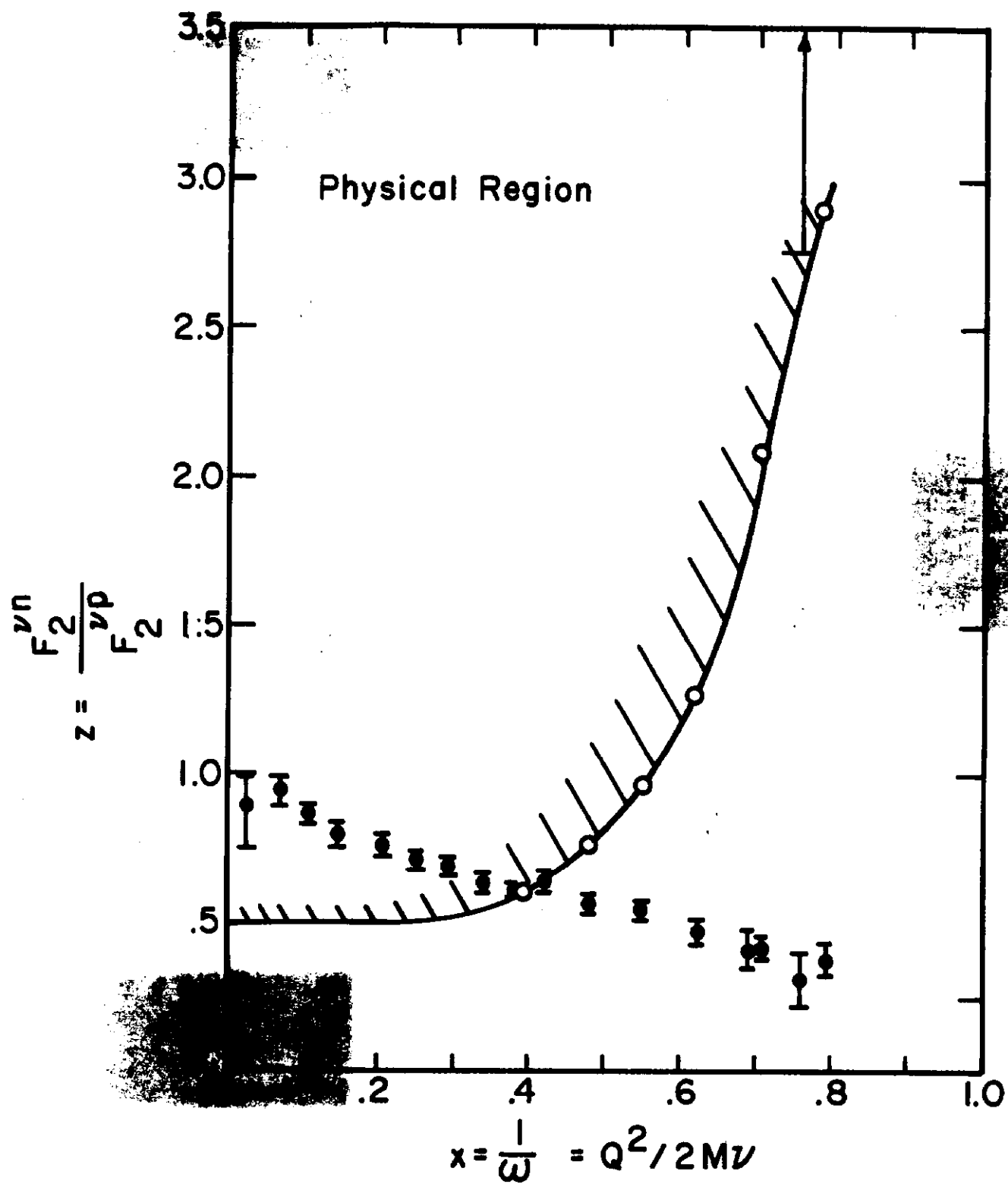
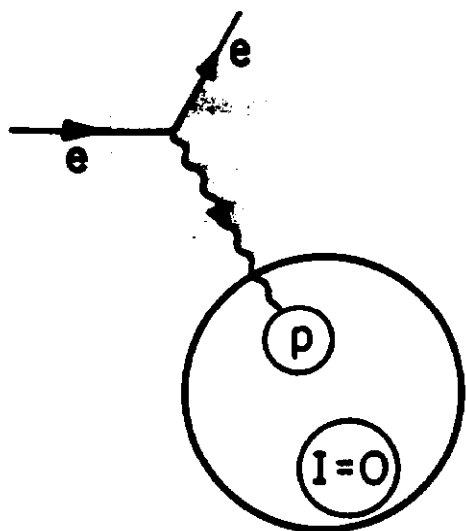
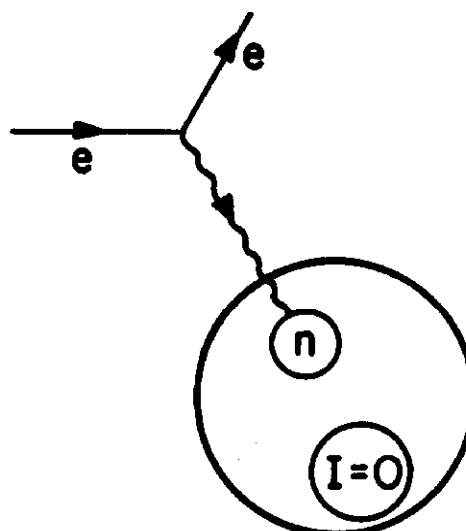


Figure 7

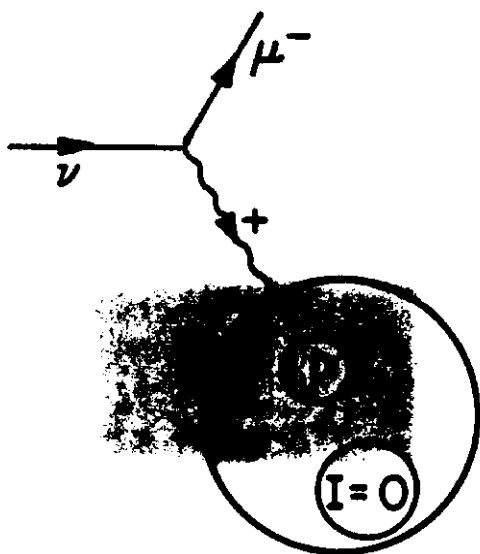


Proton

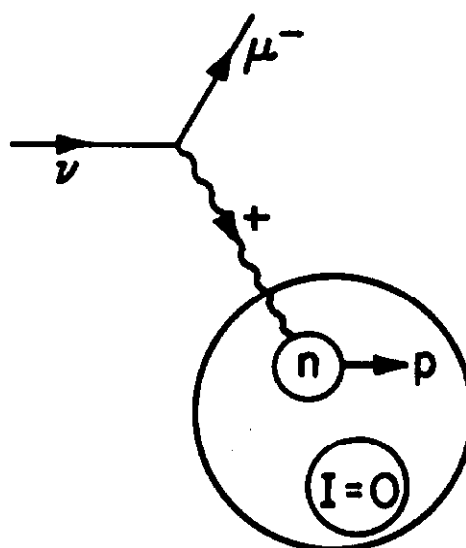


Neutron

$$\frac{F_2^{\gamma n}}{F_2^{\gamma p}} = \frac{\frac{1}{9} f_p(x) + (I=0)}{\frac{4}{9} f_p(x) + (I=0)}$$



Cannot Go



O.K.

Figure 8

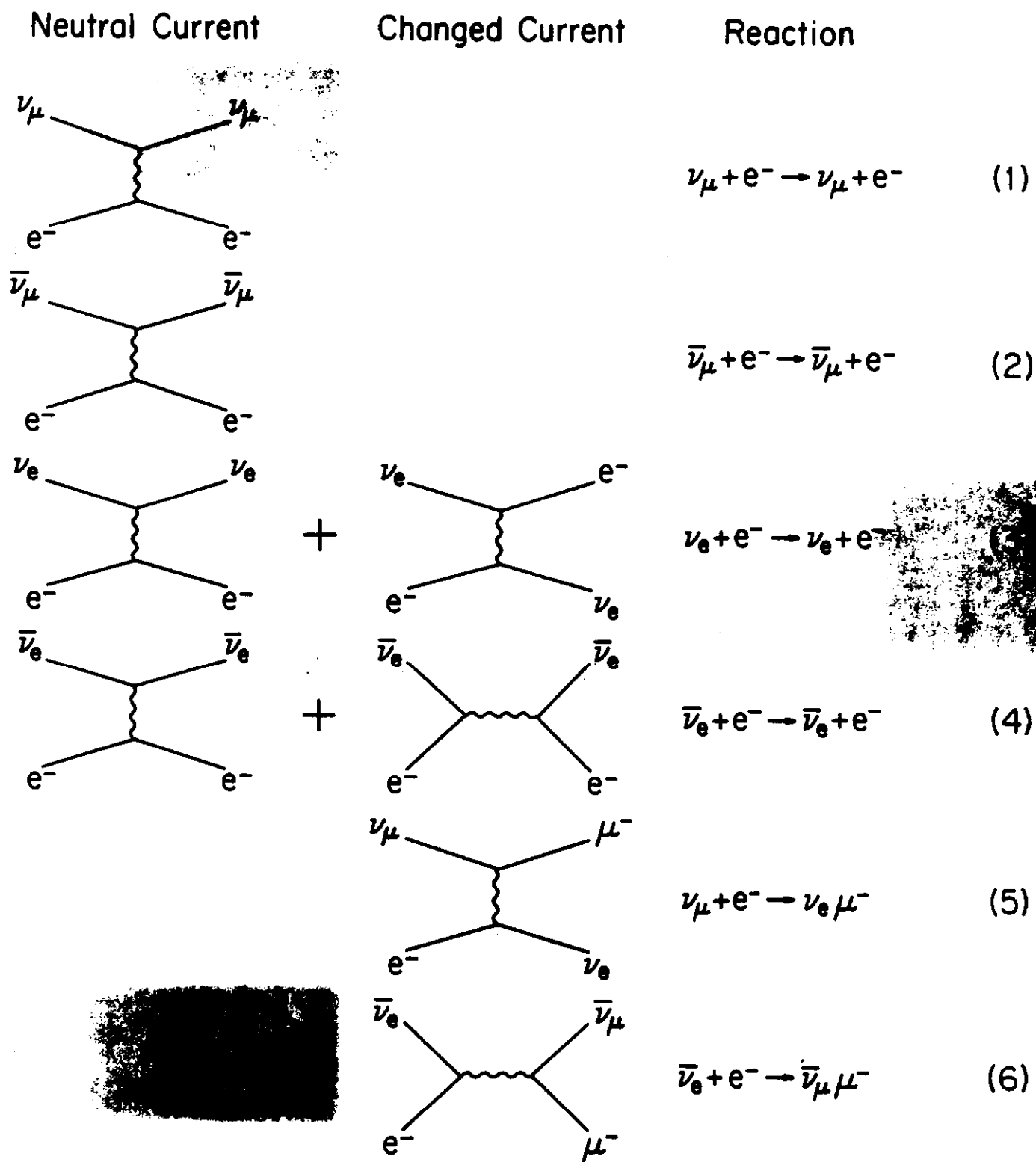


Figure 9

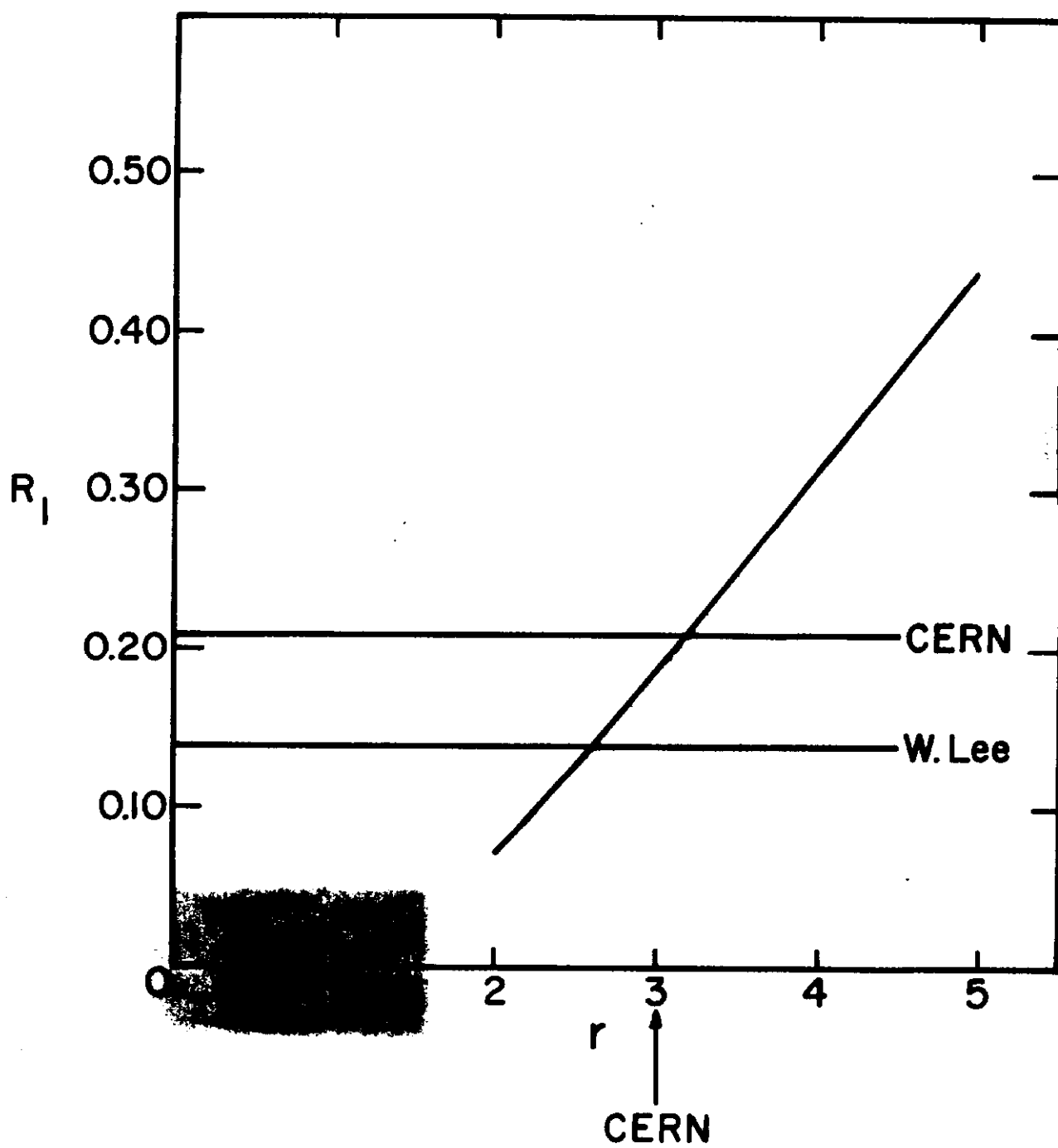


Figure 10

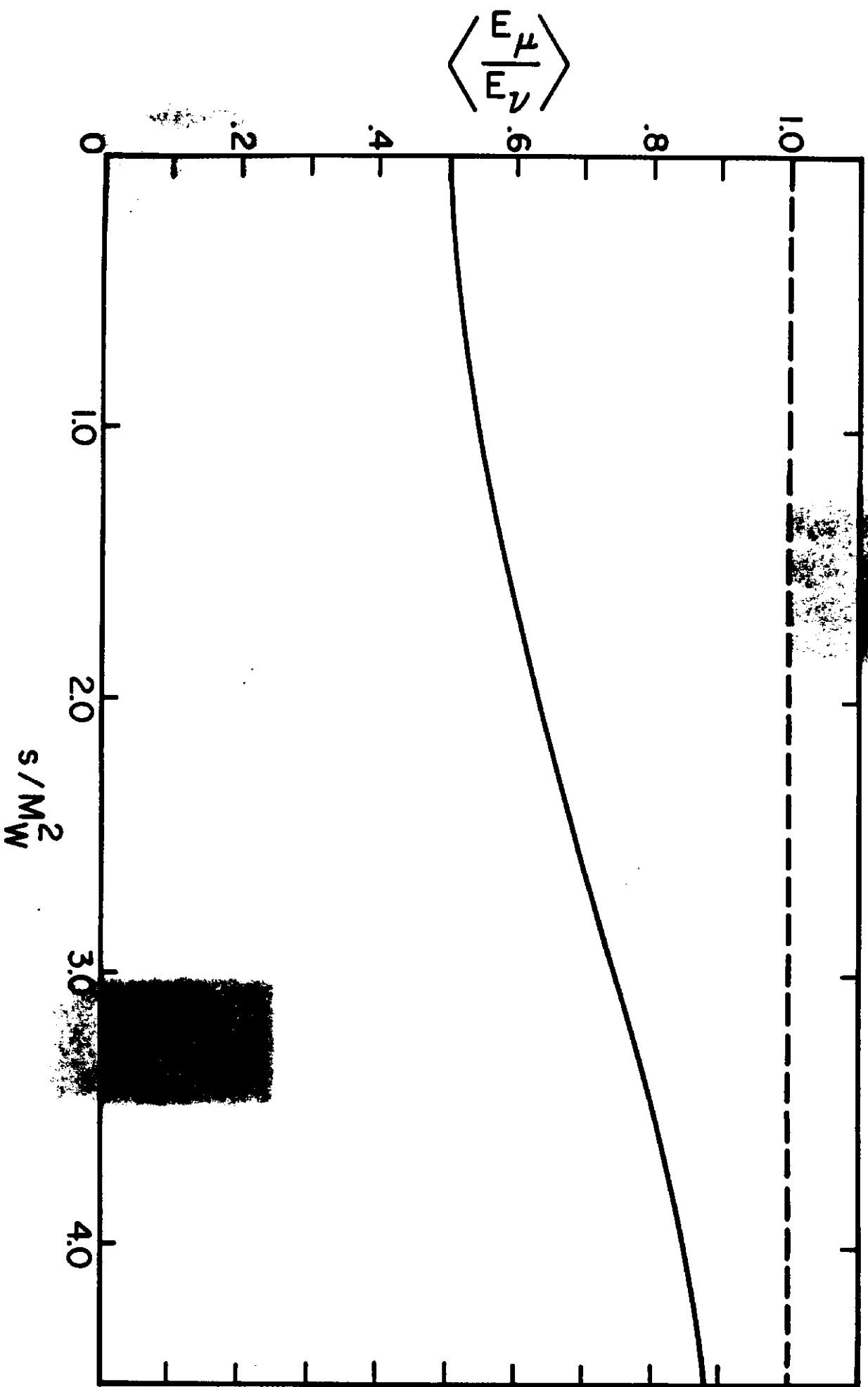


Figure 11

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~~show~~ <sup>horizontal</sup> the experimental upper bounds.
11. The mean energy of the muon in the presence of an intermediate vector boson as a function of  $S/M_W^2$ .